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A Review of Steel Properties at Low Temperatures

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17. Abstract The summary report assembles world-wide information on the use of steels for low temperature situations with particular reference to brittle fracture. A review of the state-of-the-art was conducted based on the following eight main topics: 1. environmental conditions in Arctic waters 2. present low temperature steel standards for ships 3. current experience with steel for low temperature usage 4. existing codes for use of steel in low temperature and Arctic conditions 5. steels available or under development 6. current method for checking steel for low temperature use 7. crack arrester philosophy 8. techniques used to test welding procedures. The report proposes the selection and definition of test procedures required for the evaluation of the fracture related properties of steel and weld metal and their application in a fracture control plan. The report also develops a possible "risk" methodology for the selection of the various grades of steel to suit the structural needs and temperature conditions of different locations and operational situations.			
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1. INTRODUCTION

In establishing the Arctic Shipping Pollution Prevention Regulations (ASPPR), the Canadian Government has undertaken an initiative towards specifications, regulations and standards to control the construction of ships which will operate in arctic waters.

Of particular concern in this respect are the brittle characteristics of steel behaviour at low temperatures. Grades of steel have been developed which maintain their toughness in cold conditions, but their costs are significantly higher than common structural steels.

With this concern, concepts of effective specifications and regulations are necessarily based on integrated considerations to include not only the materials requirements, but the fabrication and construction techniques, the structural configuration, and an approach based on probability and risk analysis for the design loadings and allowable stresses.

To assist the Canadian Coast Guard in drafting the necessary regulations, the Transportation Development Centre awarded a project to review the behaviour of steel under low temperature conditions. This project was undertaken by FENCO CONSULTANTS LTD. in conjunction with Lloyd's Register of Shipping.

The objective of the review is to assemble world-wide information on the use of steels for low temperature situations as required for regulations to be prepared. These must define safety requirements with respect to the low temperature properties of steel and its weldments, production control and routine inspection of the fabricated steel material. They must also recognise that many kinds of ships may be built to arctic standards for a wide spectrum of commercial and government service in the north.

2. STATE-OF-THE-ART REVIEW

2.1 Environmental Conditions in Arctic Waters

The operation of ships and the performance of structures in the Canadian arctic requires significant modifications of the design, construction and testing methods used in moderate climates. To develop and set out regulations for arctic vessels requires a thorough knowledge of the environmental conditions.

The report reviews the major problems encountered by ships in the arctic including very low temperatures and severe ice conditions. For many of the steels being used in ship construction, temperatures encountered in arctic areas during the winter months are below the transition temperatures at which the steels lose their toughness and become brittle. Stresses due to impact with ice further affect the fracture behaviour of the material. Hence, a knowledge of ice conditions and likely impact forces in various areas of the Canadian arctic is essential in determining requirements for ship construction.

2.2 Present Low Temperature Steel Standards for Ships

Traditionally, standards in merchant ship construction have been established by the classification societies. These societies, operating independently of ship builders and owners, have issued rules against which most aspects of ship design and construction can be assessed. The nine leading societies are members of the International Association of Classification Societies (IACS) which co-ordinates their activities and formulates common rules published as "Unified Requirements". As a necessary part of their activities, the societies issue specifications for materials requirements covering a range of relevant ferrous and non-ferrous materials. The report presents a review of existing steels for hull structures and other purposes under the following headings:

- . Unified Requirements - Hull Grade Steels
- . Carbon-Manganese Steels With Improved Toughness
- . Nickel Alloyed Ferritic Steels for Low Temperature Use
- . Present Canadian Steel Codes and Standards

The report indicates that steels are being produced in Canada which show characteristics satisfactory for shipbuilding and other applications in the arctic without the need for any dramatic break-through development.

2.3 Current Experience With Application of Steels for Low Temperature Usage

For ships operating for long periods in low air temperatures and in severe ice conditions, the material requirements for exposed structures require special consideration. In general, for temperatures down to approximately -25°C , normal hull steels are acceptable to the classification societies, and for thin plates (below 12.5 mm) they may be acceptable down to -40°C .

For design temperatures between approximately -25°C and -55°C, C-Mn steels are generally required and for service below -55°C, nickel steels or austenitic stainless steels are required.

The report discusses the weldability of steels and the extra requirements in terms of preheat and welding consumables depending on the parent metal and the ambient temperature when welding takes place.

The review finds that relatively few incidents of brittle fracture have been recorded since the introduction of notch tough steels. Those that have appeared were initiated by defects, usually in welding and sometimes in secondary structural members.

The failures do not, in general, indicate any need for change in the classification societies' rules for materials requirements in terms of grades of structural plates or sections. However, more rigorous requirements are being developed for the prevention of 'built-in' defects, particularly in welds. The failures indicate the importance of crack arresters and the need for attention to high thermal stresses caused by large temperature differences through or across plates. For specific arctic applications, the selection of high quality steel should be advocated and rigid quality control of the material should be programmed.

For land based structures, there are several steels suitable for use in low temperatures, for either general or specific fields of application. These include normal steels, carbon manganese and low alloy steels. The report reviews railroad applications, the pipeline industry, the storage of low temperature liquids and power transmission lines.

In selecting steel for arctic construction, welding and low-stress fracture are two important factors. Since welding can potentially damage steel, the heat input should be kept in a controlled range. The relationship between weld input, base material composition and hardness must be optimized.

2.4 Existing Codes for Use of Steel in Low Temperature and Arctic Conditions

With increasing resource development and the need for steel structures in the arctic, it had been recognized that existing codes and specifications did not provide adequate coverage for anticipated service conditions. Existing codes were supplemented by users based on their personal observations, conclusions and specific research programs. The concept of fracture mechanics emerged and introduced the application of fracture control plans which can be directly adapted to stress analysis and materials selection. Fracture control plans complement the codes and specifications developed for conventional climates.

The report reviews the basic elements of fracture-control:

- . To lower design stresses.
- . To minimize stress concentrations.
- . To use materials with improved notch toughness.

The stringent demands for engineering performance in the arctic have resulted in a new concept for specifying materials requirements. The requirements now refer to integrated systems and not to materials only as in more conventional applications.

2.5 Steels Available or Under Development

The report identifies the steel types and grades currently available which provide properties of weldability, toughness and ductility in low temperature conditions. This includes steels of the microalloyed and high strength and low alloy (HSLA) types in thicknesses up to 100 mm.

In the immediate future, development will be focused on a gradual improvement in the toughness and weldability of both low carbon microalloyed and HSLA steels. This becomes possible with improved procedures:

- . Increased use of "cleaner" steels giving enhanced through-thickness properties.
- . Increased sophistication in the thermal mechanical treatments given to the plate during production.

The study concludes that metallurgical developments are not likely to have a revolutionary effect on present day design rules for low temperature services. High yield strength steels are already available with good low temperature toughness properties although specific procedures must be applied in their use. The extra care required in fabrication and construction adds significantly to the cost.

2.6 Current Methods for Checking Steel for Low Temperature Use

Over the past thirty years, several test methods have been developed to assess the resistance of materials to brittle fracture. Many of these have lost favour either because they have been replaced by more informative tests, or because they have been too costly, or for a variety of reasons they have failed to gain wide acceptance. The report reviews the more widely accepted and relevant test methods in use today:

- (a) Assessing the possibility of fracture initiation from an existing flaw:
 - . The Charpy Test.
 - . The Drop Weight Nil Ductility Transition Test.
 - . The Dynamic Tear Test.
 - . The Wide Plate Test.
- (b) Allowing that initiation may occur and assessing the resistance of the material to fracture propagation:
 - . Linear Elastic Fracture Mechanics (LEFM) Testing.
 - . Crack Opening Displacement (COD) Testing.
 - . Charpy 'V' Notch Energy Correlations.

2.7 Crack Arrestor Philosophy

The report examines the techniques available to control fractures in structures and describes the mechanism which propagates a fast fracture. A brief summary is presented of the history of fractures in ships with consideration of the changes in steel quality and the gradual adoption of the crack arrester principle.

The energy to propagate a fracture is derived from the region of the crack tip and once such a condition has been produced only a radical change in the conditions will cause the crack to terminate. A crack will stop at a free edge and also in a material that is tough as opposed to one that exhibits brittleness. As examples of these two crack stopping methods:

- . A riveted seam could constitute a free edge in the plate containing the fast fracture and, therefore, prevent further progress of the crack.
- . A strike of plating of tougher material in the path of the crack could achieve the same effect.

Such design features are described as crack arrester systems and have been developed for a number of engineering activities including ship construction, aircraft structures, oil and gas transport piping, and all-welded oil storage tanks.

Ship structure design has no procedures for the specification of crack arrester designs. Each classification society has its own requirement, developed largely by experience and not by theoretical considerations.

In recent years, developments in fracture mechanics have attempted to solve this problem with comparative studies. Using linear fracture mechanics techniques it has been possible to derive the necessary toughness properties of an arrester strike to prevent a crack passing through it.

2.8 Techniques Used to Test Welding Procedures

The report reviews the standard requirements for the validation of welding procedures which are included in a variety of codes, such as CSA, AWS, BSI, ASME, etc. The common mechanical test requirements in these codes call for bend tests, tensile tests for yield strength, ultimate tensile strength and elongation, and Charpy tests in the weld metal and other specified positions in the weldment.

The first requirement of these tests is to ensure that the test welds are fully representative in terms of material, heat input, procedural details and structural restraint. For metallurgical and mechanical reasons it is important that the test specimens are in full section thickness and that a representative sharp defect should be present.

It is concluded that the approach to construction of arctic service ships should be modelled on pressure vessel quality standards, and that it would be appropriate to adopt a quality plan method of control covering all aspects of the construction in detail. Lloyd's Register of Shipping is at present considering these aspects of arctic vessel construction, and a tentative standard is being developed.

3. SELECTION AND DEFINITION OF TEST PROCEDURES

3.1 Introduction

The test procedure recommended in the report is based on the premise that the minimum design temperature is -50°C . However, the method is flexible enough to give guidance to material selection at any temperature level. Comments are predominantly aimed at hull structure weldments. This is the area most at risk due both to the possibilities of defects arising and uncertainties with regard to toughness.

3.2 Charpy Testing

The selection of steels with respect to brittle fracture risk in the United Kingdom, Japan and most European countries is based largely on Charpy 'V' notch testing. The application codes require specific performance levels related to design temperature, thickness of the component and stress conditions. These requirements are generally empirical and to a large extent based on experience.

The report recommends that:

- Charpy testing should be retained as an acceptance criterion, and specific energy levels required at the operating temperature.
- Care should be taken in the selection of Charpy and other specimens, with the intention of attempting to identify the least tough region.
- Charpy 'V' notch transition curves should be obtained at the procedural test stage to permit a relationship between COD/LEFM and Charpy values to be established. These Charpy values can then be used in production as quality control checks to ensure adequate toughness levels are being attained in production welds, and parent plate.

3.3 COD Testing

The report recommends a materials validation route using the crack opening displacement (COD) approach. It can be used as the basis for a logical and non-restrictive fracture-control plan in that some form of quantitative judgement can be made between materials, and it will enable an assessment to be made of allowable defect sizes. COD can also be directly applied to a risk assessment in a way not possible using other approaches. Inspection would be aimed at finding quality control defects of a size exceeding those calculated to cause brittle fracture.

The COD approach is based on observations that a crack, under the action of a tensile load normal to the crack plane, opens at the tip to give a crack tip displacement. It was postulated that this displacement must reach a critical value prior to the crack propagating either slowly (ductile tearing) or in a fast, unstable fashion.

This approach provides the basis for the recently published British Standards Institute Document PD 6493, which deals comprehensively with the derivation of acceptance standards. Rules are given for the conversion of various defect types into a standard nominal through-wall defect and thence

to an acceptable/non-acceptable decision. Rules on defect interaction, stress considerations and other details are given. The COD methodology has been accepted by some regulatory authorities in the U.S.A., Europe and Japan.

Of the other test methods considered in the report, only the Pellini drop weight test and the instrumented Charpy Test are considered convenient enough to be usefully employed.

4. AN APPROACH TO RISK ANALYSIS FOR THE SELECTION OF STEELS

4.1 Introduction

The report outlines the development of a methodology for the selection of steel for arctic usage with a simple fracture mechanics approach involving stress, defect size and material toughness. By defining the conditions for a fast fracture to occur, it is possible to quantify this risk in association with the chance occurrence of major parameters including temperature. An extensive program of data acquisition will be required over several years before such a procedure can be applied.

In the past, the design requirements for ship structures have been based largely on experience and deterministic methods. However, in recent years, following the trend set in other industrial fields, there has been steady progress towards probabilistic techniques, which set out to quantify the precise risk involved in respect to a particular event occurring.

Because of the randomness of loading situations in actual service, precise definition of a design condition could be meaningless as it may represent only one of a multiplicity of load configurations. It could be a condition with a very low probability of occurrence. The overall risk involved cannot be quantified unless all load situations together with their individual risks are considered.

A true risk assessment procedure attempts to quantify a meaningful risk and provide a model for comparison with known experience. In addition, this can be used to calibrate the theoretical procedure to improve its prediction capabilities.

The selection of steel properties for different arctic environments is suited to the risk assessment approach. This part of the report develops a suitable mathematical model of the risk equation. This could be used to evaluate different ice areas and be calibrated with structural failure statistics.

4.2 The Risk Concept

The report reviews the acceptance of risk in relation to ship operation in the arctic. Statistics of failure for ships in world-wide operation are presented and discussed in relationship to the hostile nature of the arctic environment and the remoteness and inaccessibility of the ship in the event of damage occurring.

4.3 The Failure Problem

While fatigue can produce fractures and exacerbate any defects present in both the parent material and the welding, the major problem concerns a catastrophic failure resulting from a fast fracture being initiated. The occurrence of such an event depends on a large number of factors, but the three main ones are as follows:

- . A stress raiser present, such as a defect or a notch.

- . A level of induced strain or stress in association with the geometry of the defect, at least equal to the critical fracture toughness of the material.
- . Toughness quality of the material containing the defect.

In the report, a simplified fracture assessment mechanism has been developed relating the major factors contributing to fast fracture initiation probabilistically in a risk assessment approach. This approach could be used to improve safety in low-temperature environments.

4.4 The Major Model Parameters

The model presented in the report is based on a simple stress pattern, pure tensile strain in the deck augmented by the effect of stress concentration. While more complex stress situations are obviously present in the ship's structure which could give rise to a worse stress/strain situation, their specification would be extremely difficult. Since the aim of the study is one of comparative behaviour, a simple approach is justified.

The different stresses induced in the deck are as follows:

- . Residual "locked-in" stress.
- . Still-water stress.
- . Temperature-induced stress.
- . Wave-induced stress.
- . Impact stress (slamming or ice impact).
- . Springing.

The important difference in the characteristics of the various stress components lies in the rate at which the stress cycles change, the impact stress representing by far the worst rate at which stress is applied.

The major unknown component is the ice impact stresses where there is a lack of long-term data. While several investigations have been carried out which might provide a general level of stress, measurements are not readily available to provide statistical information.

The two steel properties of major interest to the fracture model are the yield strength of the material, and toughness. Both vary with temperature.

4.5 Probabilistic Character of the Parameters

The parameters discussed in the previous section fall into two categories: those which are time related and those which are not. The former group includes temperature and stress, the latter includes mechanical properties, structural defects and their stress concentration factors.

The main time related parameters are controlled by the environment, and, therefore, are dependent on the area in which the ship is operating.

Both the probabilities of stress and temperature will normally be expressed in terms of cumulative probability, which gives the probability of exceedence.

4.6 The Basic Risk Model

The development of a 'total ship' model for risk analysis is considered an extremely complex problem. The alternative is to use a single plate member for comparative studies until such time as some correlation can be established between real risk for the whole ship and the hypothetical structural element. This plate, containing a weld, would represent a component part of the ship and could be assigned a range of defects and material toughness properties appropriate to specific parts of the ship's structure and to the plate thickness examined. Obviously, different thicknesses of plate could have different defect sizes and material properties. Stress level patterns, could be established for each specific location.

5. CONCLUSIONS

Data presented in the report indicate the nature of the conditions to which ships are subjected when operating in arctic waters. While these conditions are severe, they are by no means unique, and a significant number of engineering structures have been constructed for similar environments. The study has clearly identified that there is a need for more rigorous requirements for ship structures in respect to fracture control where operating in arctic winter conditions.

The review has investigated a wide range of steel grade properties, both for specific marine and non-marine usage, and has identified those having good toughness properties at low temperature which are available in Canada. In addition, there are numerous proprietary steels with enhanced toughness properties produced by complex thermo-mechanical treatments in Canada at the present time.

It is concluded that there is no immediately apparent limitation to the construction of arctic service vessels due to a lack of suitable steels. With due consideration to design and construction standards, existing steels could be utilized with established fabrication and welding practices. In some instances, the use of these steels may require quality control of welding and inspection in excess of those at present adopted in the ship building industry.

Even if relatively sophisticated steels are required in limited cases for arduous situations, it is not expected that insurmountable problems would arise in their welding and fabrication.

The basis of fracture control at low temperature is outlined with discussions of the trend to a more quantitative approach. This can be tied in with specific design requirements by the application of yielding fracture mechanics tests. In more environmentally sensitive or hazardous situations, these techniques have been applied widely. The basis of this approach seeks to evaluate the resistance of the steel to fast fracture initiation.

To control and limit damage due to fast fracture, adequate toughness must be provided through control of design, material, welding and other manufacturing processes by means of quality assurance programs, non-destructive examination programs and provision of crack arresters in important and vital areas. This approach accepts the risk that a fast fracture could occur, and the crack arrester then plays a very important role in safeguarding the ship, its crew and its cargo.

The concept of applying a probabilistic technique to steel property requirements based on risk methodology may provide the scope necessary for a wider rational approach when statistical data becomes available. The study presents a technique based on a simple fracture mechanics approach that could incorporate this probability data and provide a useful comparative risk assessment for the selection of steels for Arctic use. Further development of the procedure requires collection of basic reliable data covering most of the important variables influencing the risk of fast fracture.